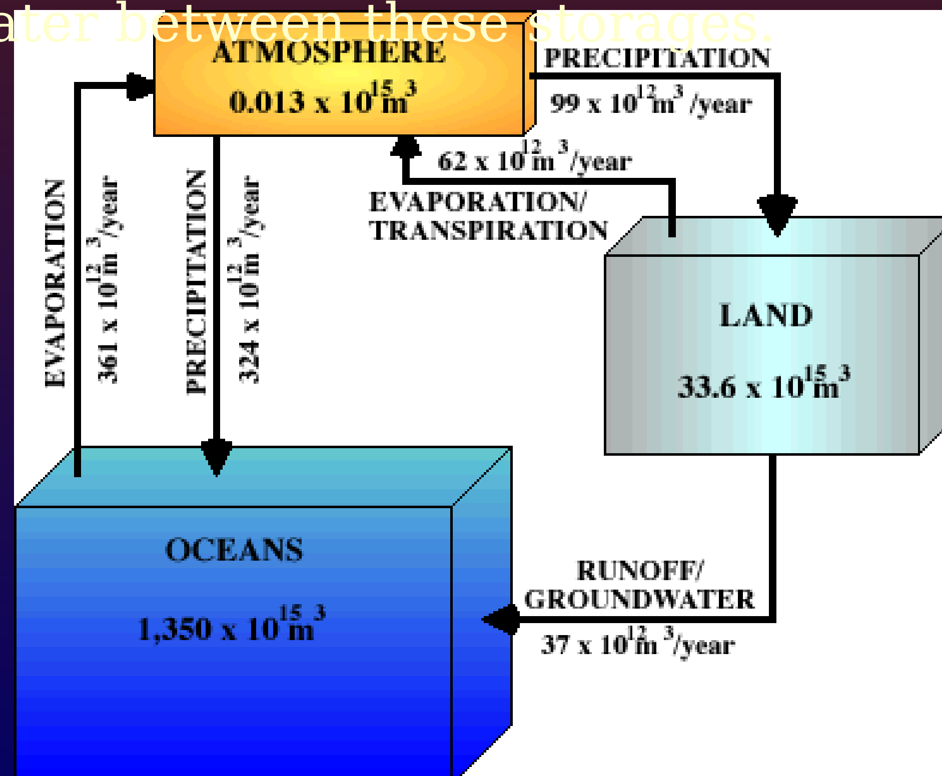
The Hydrologic Cycle

The Earth's Water Budget

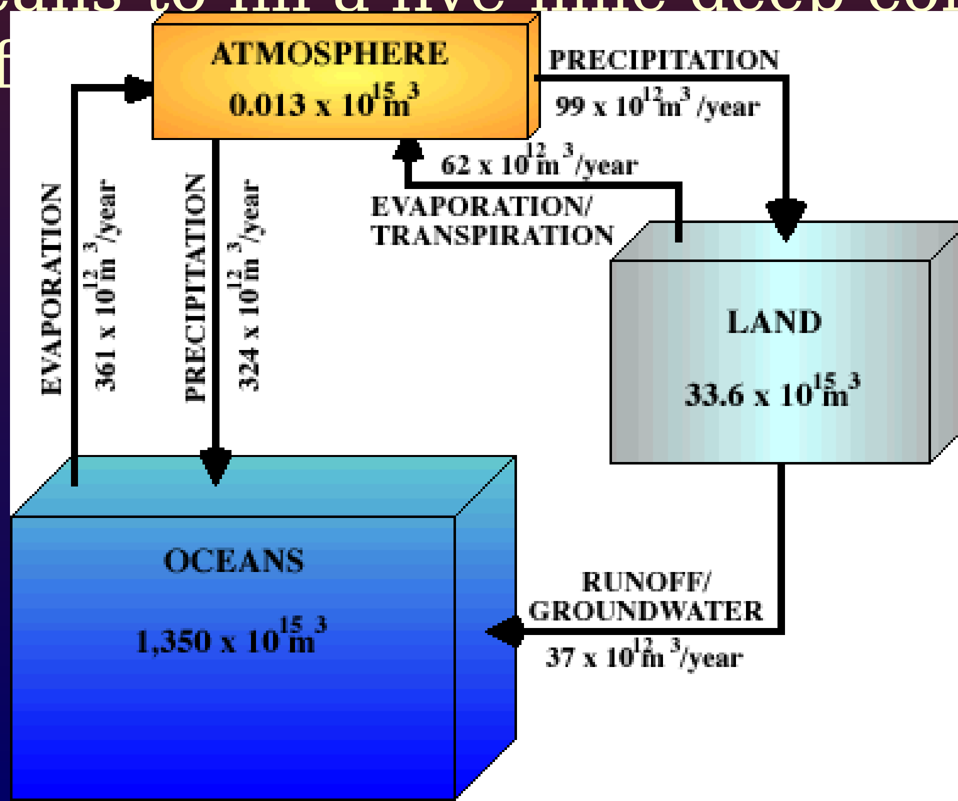
storage and fluxes

Water covers 70% of the earth's surface, but it is difficult to comprehend the total amount of water when we only see a small portion of it. The following diagram displays the volumes of water contained on land, in oceans, and in the atmosphere. Arrows indicate the annual exchange of water between these storages.



The oceans contain 97.5% of the earth's water, land 2.4%, and the atmosphere holds less than .001%, which may seem surprising because water plays such an important role in weather. The annual precipitation for the earth is more than 30 times the atmosphere's total capacity to hold water. This fact indicates the rapid recycling of water

To visualize the amount of water contained in these storages, imagine that the entire amount of the earth's annual precipitation fell upon the state Texas. If this was to occur, every square inch of that state would be under 1,841 feet, or 0.3 miles of water! Also, there is enough water in the oceans to fill a five-mile deep container having a base of

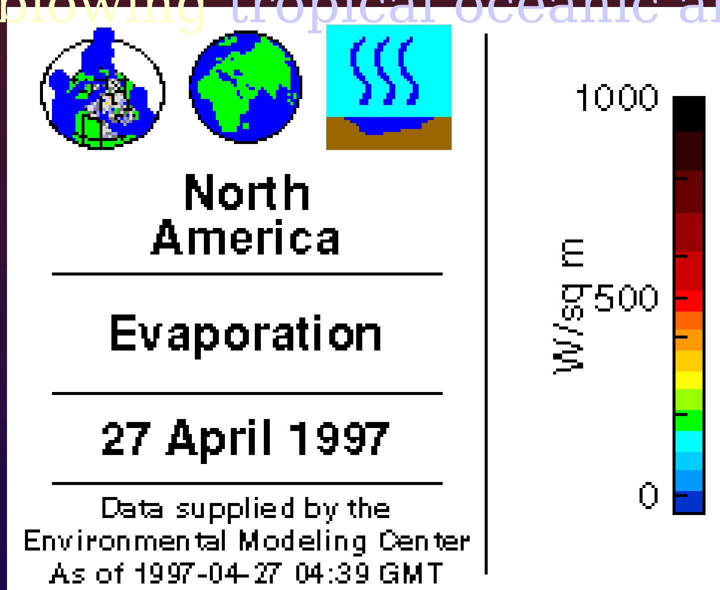


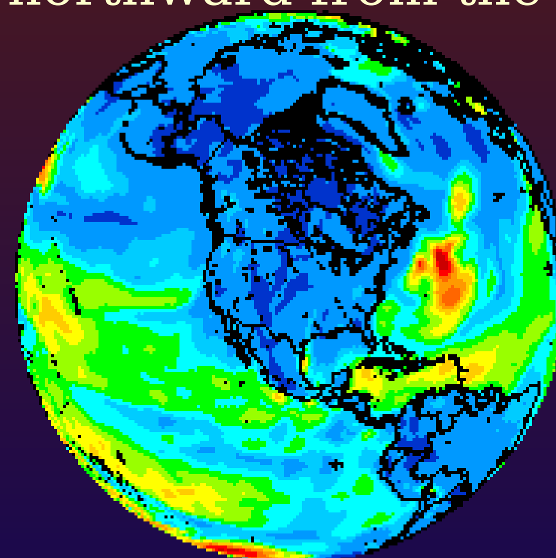
Evaporation

the conversion of water from a liquid into a gas

Water is transferred from the surface to the atmosphere through evaporation, the process by which water

Approximately 80% of all evaporation is from the oceans, with the remaining 20% coming from inland water and vegetation. Winds transport the evaporated water around the globe, influencing the humidity of the air throughout the world. For example, a typical hot and humid summer day in the Midwestern United States is caused by winds blowing tropical oceanic air northward from the Gulf of Mexico.

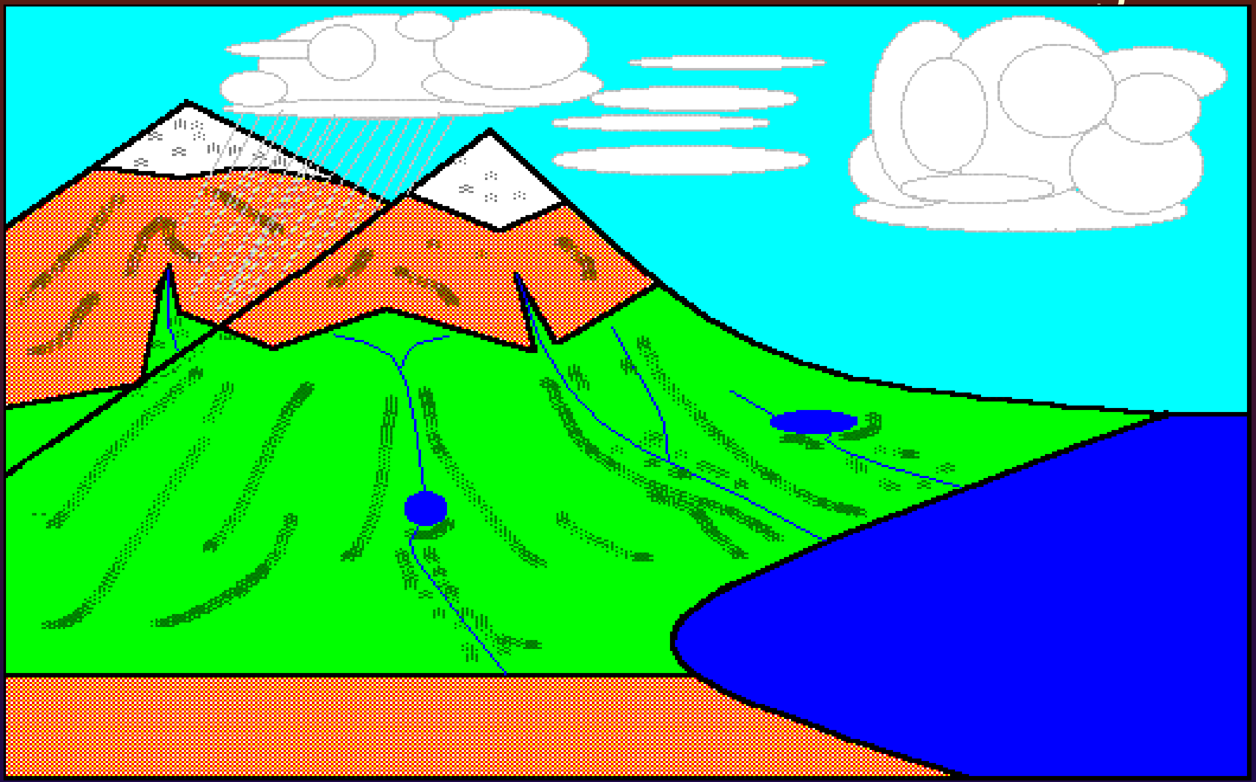




Most evaporated water exists as a gas outside of clouds and evaporation is more intense in the presence of warmer temperatures. This is shown in the image above, where the strongest evaporation was occurring over the oceans and near the

Condensation

the conversion of water from a gas

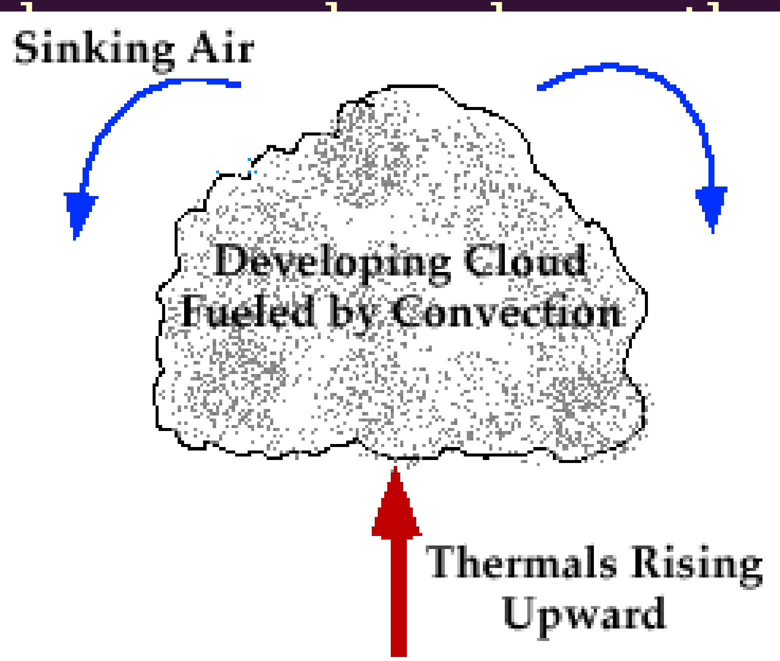


Condensation is the change of water from its gaseous form (water vapor) into liquid water. Condensation generally occurs in the atmosphere when warm air rises, cools and looses its capacity to hold water vapor. As a result, excess water vapor condenses to form cloud droplets. The upward motions that generate clouds can be produced by convection in unstable air, convergence associated with

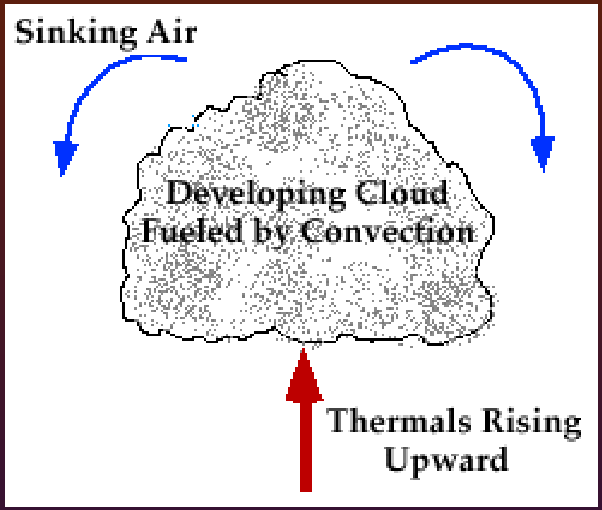
Convection

atmospheric motions in the vertical direction

In meteorology, convection refers primarily to atmospheric motions in the vertical direction. As the earth is heated by the sun, different surfaces absorb different amounts of energy and convection may occur where the surface heats up very rapidly. As the surface warms, it heats the overlying air, which gradually
n the surrounding air and begins



The bubble of relatively warm air that rises upward from the surface is called a "thermal".

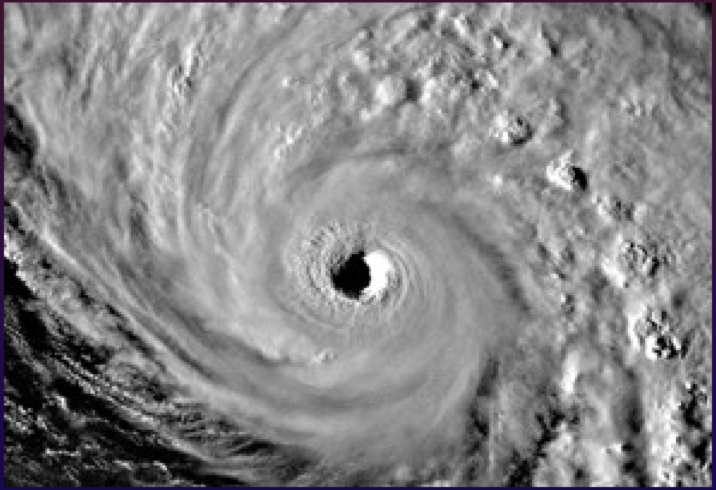


A simple demonstration of condensation through convection can be performed by placing a pot of water on a heated stove. The burner represents the heating of the earth's surface by the sun, while the water and the air above it represent the atmosphere. As the bottom of the pot (earth's surface) begins to heat the water (lower atmosphere), warmer and less dense water evaporates and rises (thermal) into the drier, colder air above the pot (middle atmosphere). This causes the thermals to co
condense, forn
that is visible a

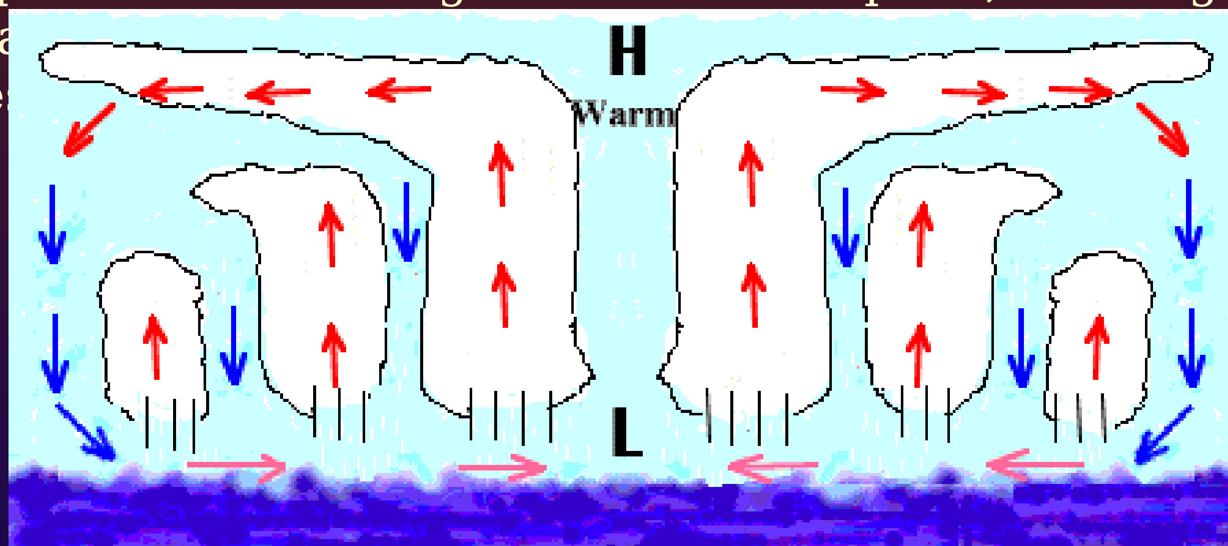
This same process occurs in the real atmosphere as the water vapor within rising thermals condenses to form a cloud, as

extra-tropical and tropical cyclones

Both extra-tropical and tropical cyclones, like this hurricane, can cause air to rise. This type of lifting is different from the lifting produced along frontal boundaries.

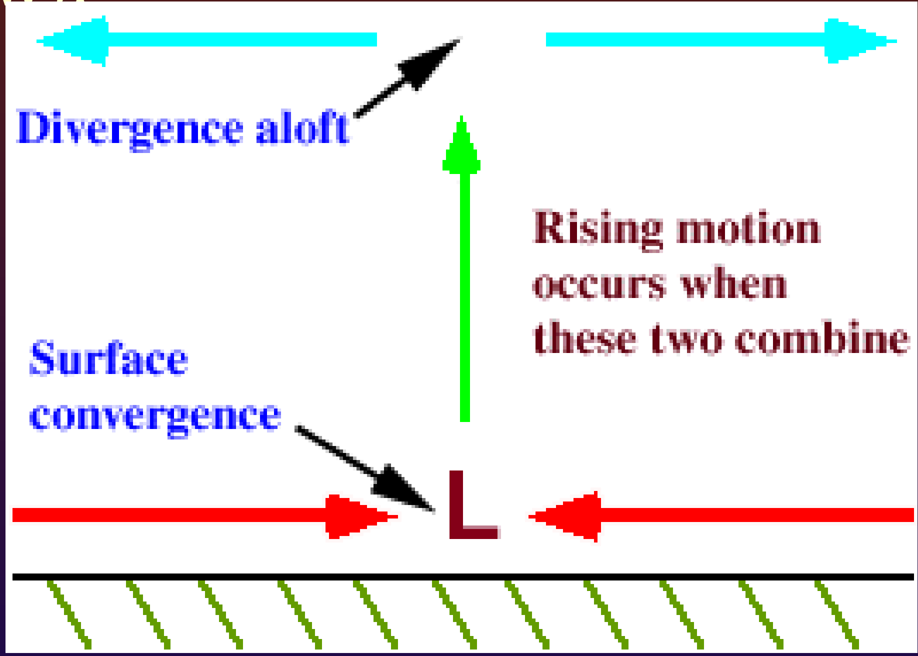


In hurricanes, condensation occurs through a process known as CISK (Convective Instability of the Second Kind). We will demonstrate CISK by referring to the animated cross-section through a mature hurricane given below. In CISK, surface convergence (pink horizontal arrows) causes rising motion around a surface cyclone (labeled as "L"). The air cools as it rises (red vertical arrows) and condensation occurs, which releases latent heat into the atmosphere. This heating causes air to expand, creating an area of high pressure a ... sure gradient cause ... ows).



Since pressure is a measure of the weight of the air above a unit area, removal of air at upper levels subsequently reduces pressure at the surface. A further reduction in surface pressure leads to increasing convergence (due to an intensified pressure gradient), which further intensifies the rising motion, latent heat release, and so on. Despite the absence of fronts, a tremendous amount of lifting occurs in hurricanes, with intense

In extra-tropical cyclones, surface winds are deflected by friction towards the center of the low pressure system (red "L" below).

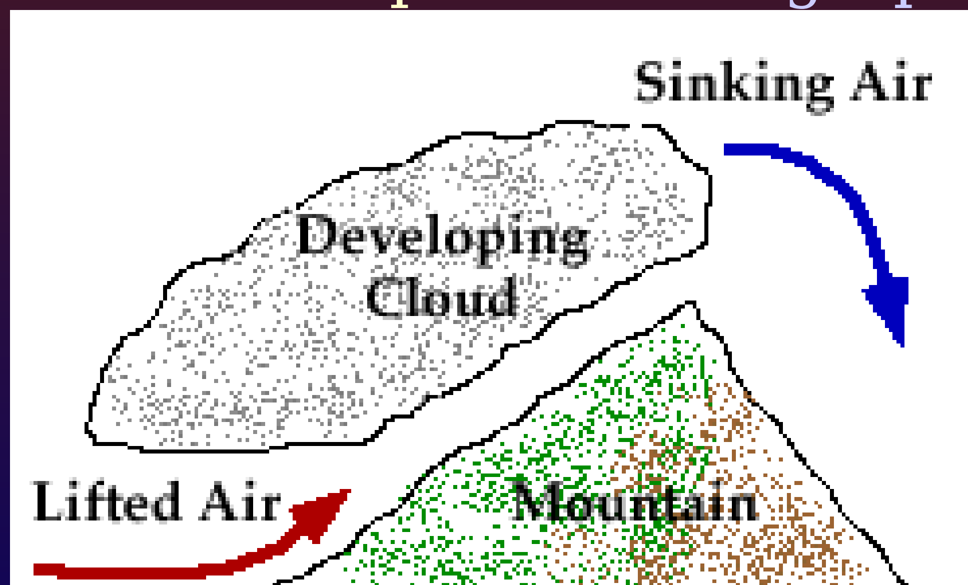


Coupled with divergence aloft, (blue arrows), surface convergence (red arrows) can generate rising motion (green arrow) that leads to the condensation of water

Topography

forced lifting by the surface of the earth

Air is also lifted by the earth itself. When air encounters a mountain range, for example, air is forced to rise up and over the mountains and if enough lifting occurs, water vapor condenses to produce orographic clouds.



In the United States, the prevailing winds are generally from west to east, so most orographic clouds form on the

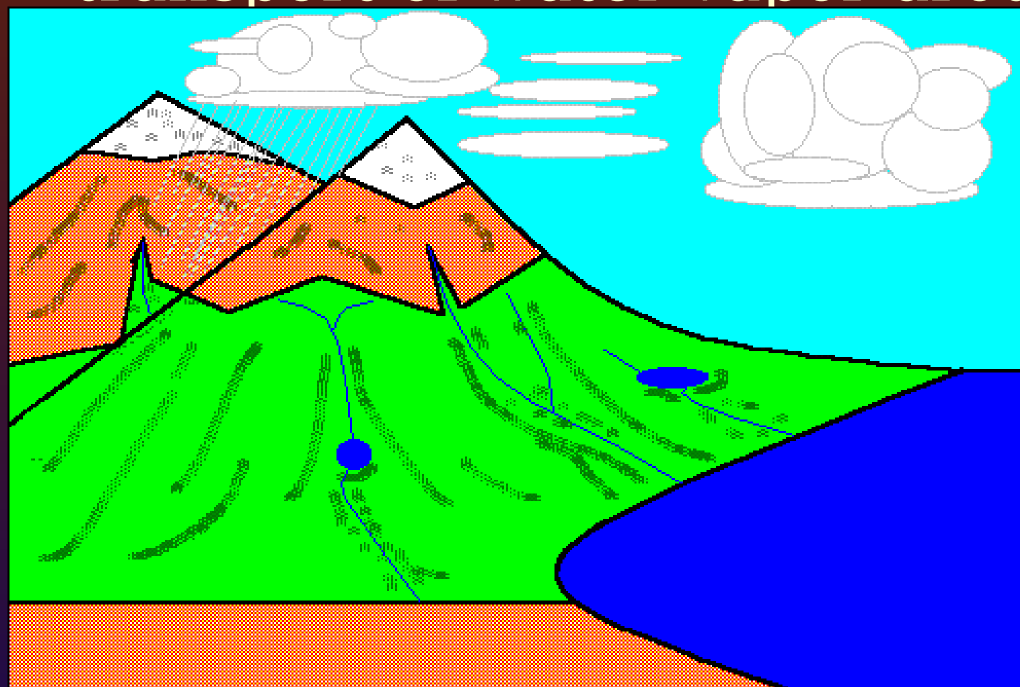
Why do orographic clouds appear to be stationary?

Air rises on a mountain's windward (upwind) side and sinks on the lee (downwind) side. This sinking motion warms the air and causes the cloud to evaporate, destroying the cloud. Therefore, even though the wind blows over the mountain, condensation processes and associated cloud droplets are confined to the windward side. This is why orographi e of the mountain and end near t

The Rocky and the Sierra-Nevada Mountains are examples of mountain ranges that produce orographic clouds. The large dark cloud in the upper right-hand corner of the picture above and the smaller cloud just above the mountain are both examples of

Transport

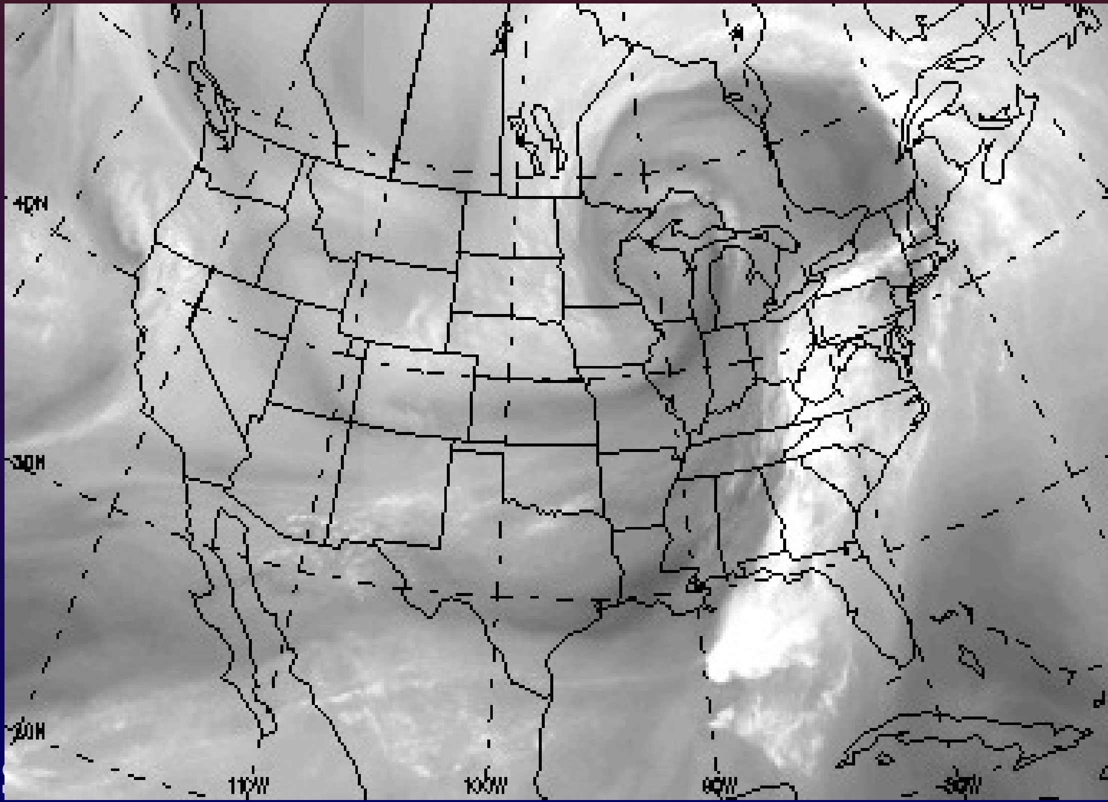
transport of water vapor around



In the hydrologic cycle, transport is the movement of water through the atmosphere, specifically from over the oceans to over land. Some of the earth's moisture transport is visible as clouds, which themselves consist of ice crystals and/or tiny water droplets. Clouds are propelled from one place to another by either the jet stream, surface-based circulations like land and sea breezes, or other mechanisms. However, a typical 1 kilometer thick cloud contains

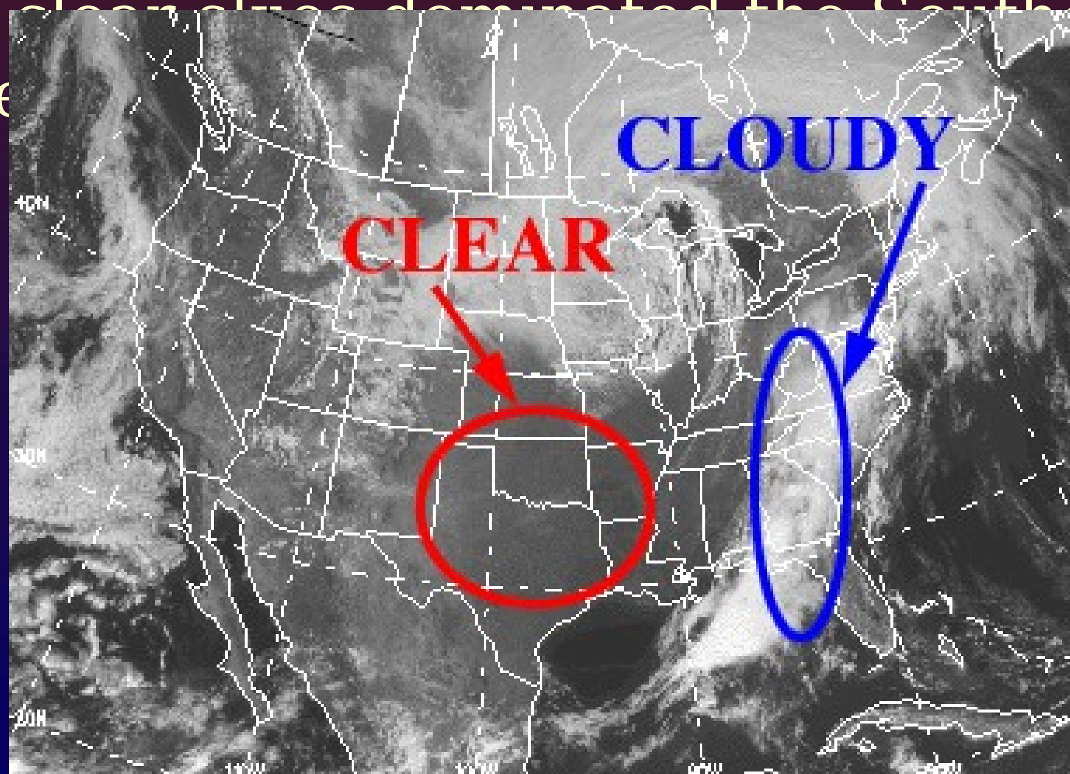
Most water is transported in the form of water vapor, which is actually the third most abundant gas in the atmosphere. Water vapor may be invisible to us, but not to satellites, which are capable of collecting data about the moisture content of the atmosphere. From this data, visualizations like this water vapor image are generated, providing a visual picture of moisture transport in the atmosphere.

Bright areas indicate higher amounts of moisture and are often associated with clouds. Dark areas indicate less moisture, or relatively drier air. However, moist air does not always contain clouds.



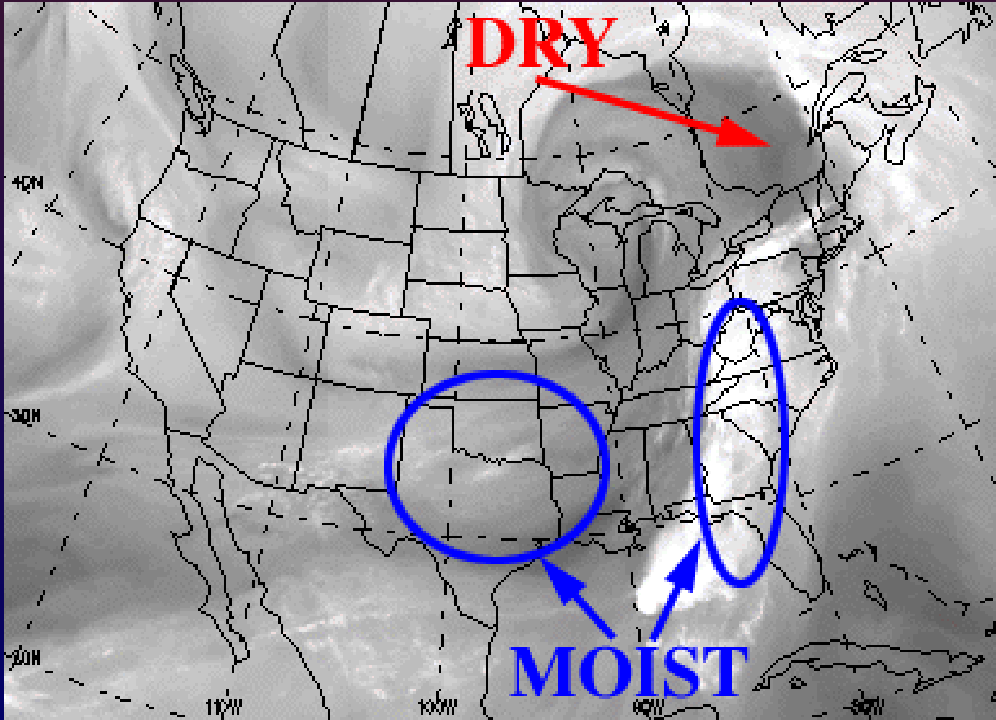
detecting the presence of water vapor

Clouds are not the only indicator of moisture in the atmosphere. In the visible satellite image below, there was considerable cloudiness associated with stormy activity over the the Eastern United States (circled in blue), while clear skies dominated the Southern Plains (circled in re



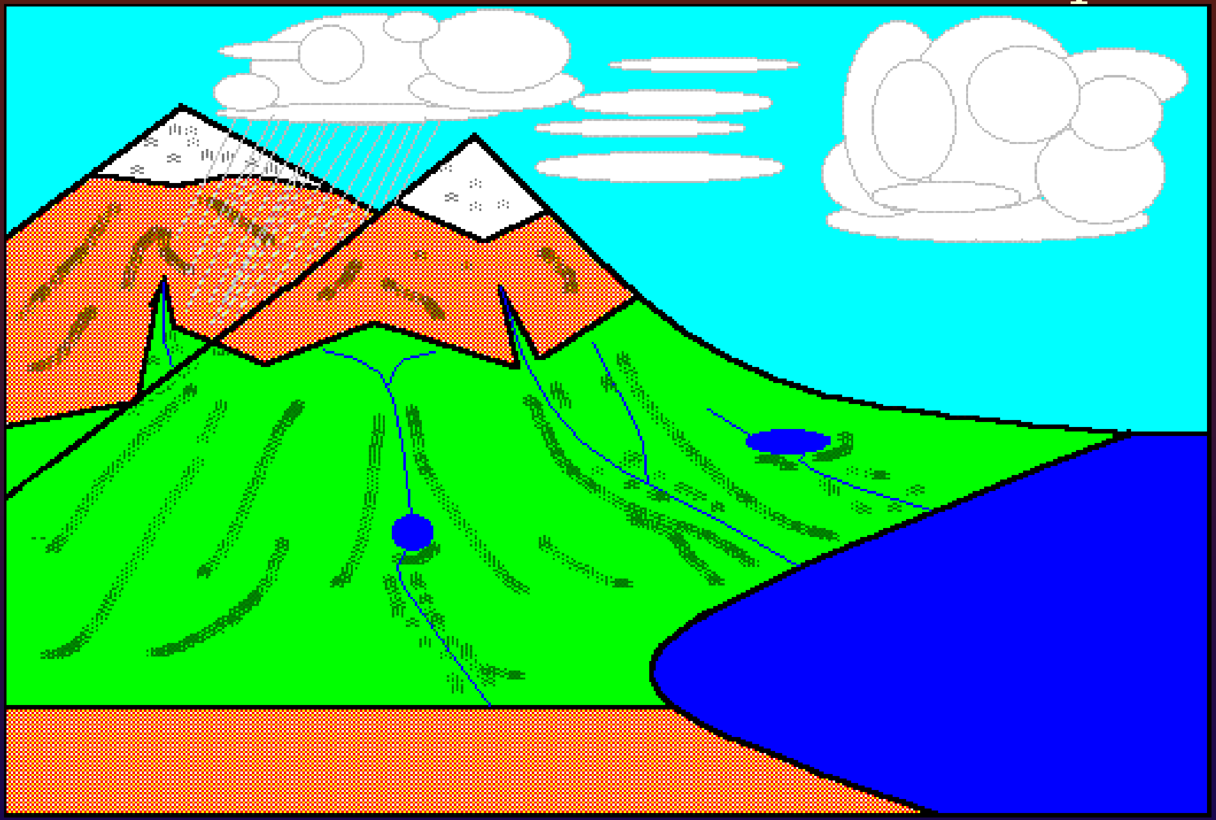
Now compare this image to the water vapor image for the same time. Bright white areas indicate higher amounts of moisture while darker areas indicate lesser amounts. The pronounced white areas in the water vapor image correlate almost exactly with the clouds circled above (in blue). However, the water vapor image indicates relatively high concentrations of moisture across the Southern Plains, while this same region appears cloud-free in the visible image. This is an example of water being transported through the atmosphere in its vapor form.

The area in the Southern Plains is not as bright as the area of clouds located in the Eastern U.S. because the clouds contain more water. Also observe that there is no black on this image, signifying the



Precipitation

transfer of water from the atmosphere

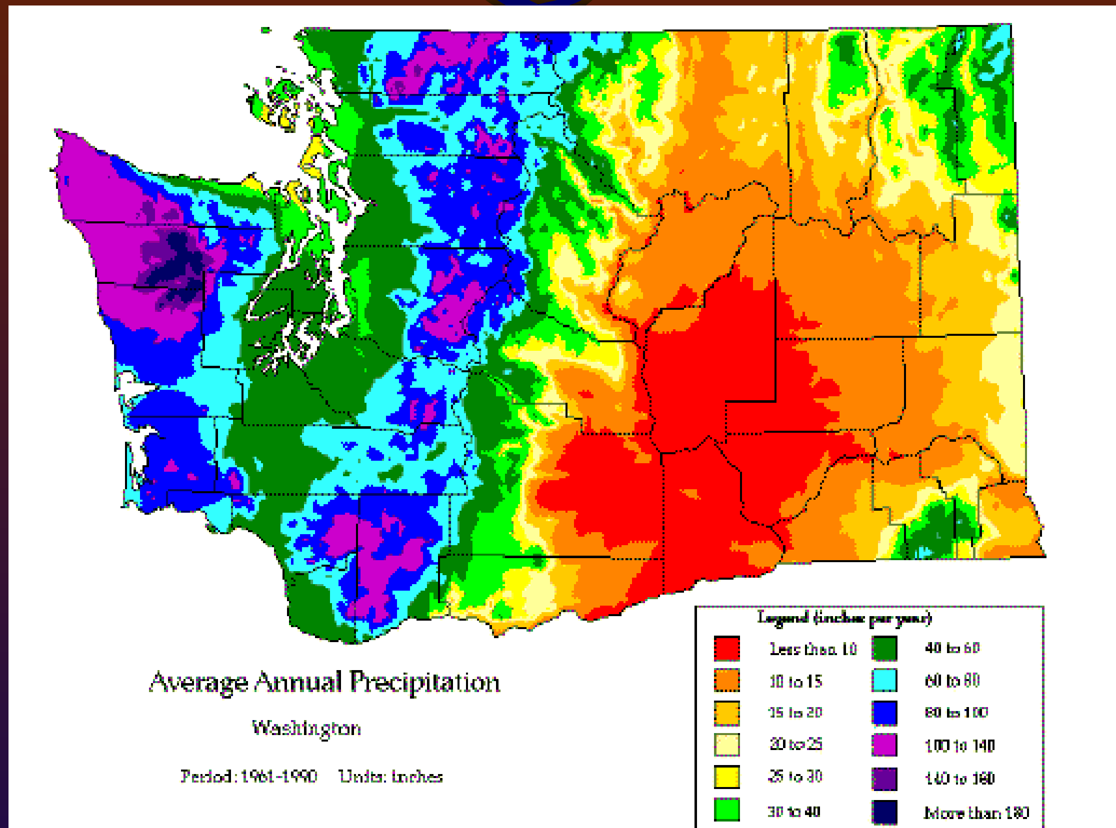


Precipitation is the primary mechanism for transporting water from the atmosphere to the surface of the earth. There are several forms of precipitation, the most common of which for the United States is rain. Other forms of precipitation include; hail, snow, sleet, and freezing rain. A well developed extra-tropical cyclone could be

Amounts of precipitation can vary by location. For example, deserts like this one in Nevada, average less than an inch of total precipitation per year.

The agricultural Midwest, however, receives approximately 15 inches per year, while tropical rain forests like this one in Hawaii, can receive more than 100 inches of precipitation per year!

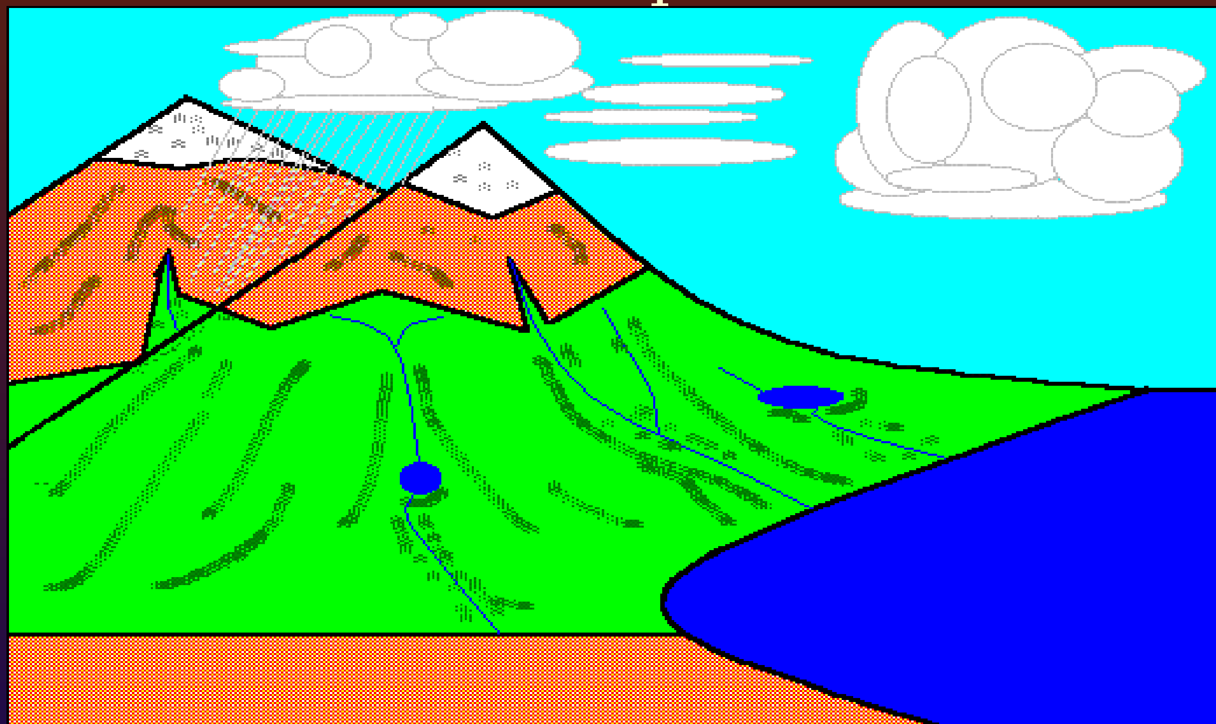
Amounts of precipitation also vary from year to year. In 1988, an intense drought gripped the Midwestern United States, disrupting agriculture because there was not enough rain to sustain crops. Five years later in 1993, the same area was subjected to severe flooding, greatly reducing the annual harvest because there was too much



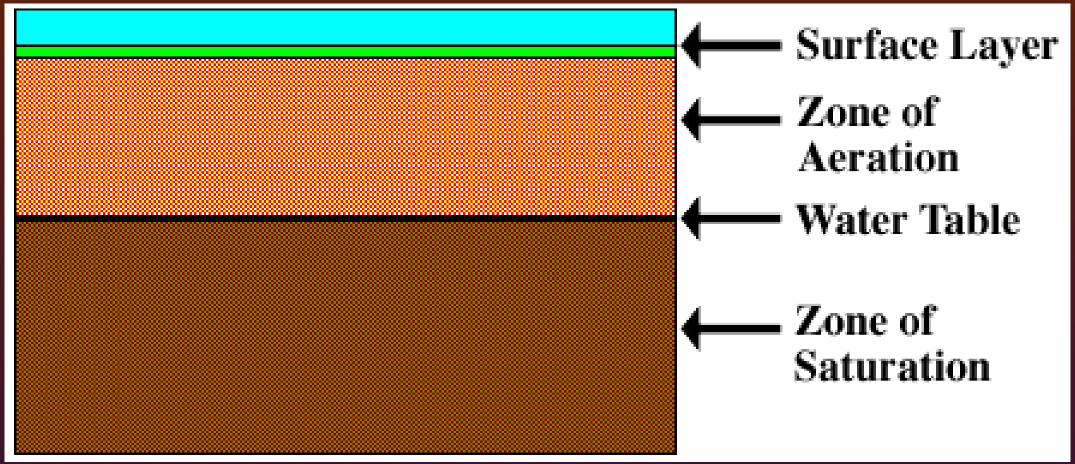
A good example of the geographical variability of precipitation is shown here in a plot of average annual precipitation for the state of Washington. Within a distance of 250 miles, annual precipitation totals change from more that 180 inches per year (deep purple) to less than 10 inches per year (bright red)! This distribution is a direct result of the topography of the land. The high precipitation totals are located on the western side of the Cascade mountains, while the

Groundwater

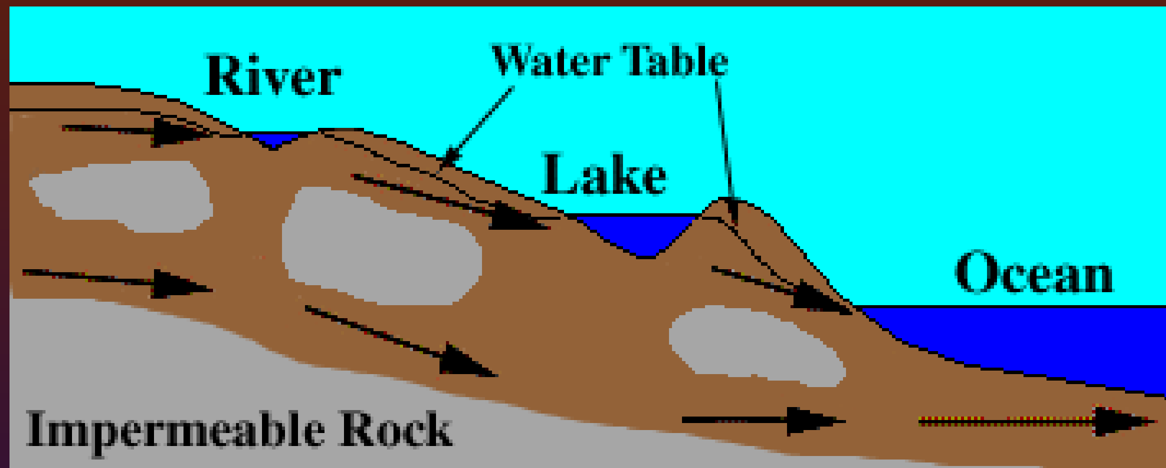
water that has penetrated the



Groundwater is all the water that has penetrated the earth's surface and is found in one of two soil layers. The one nearest the surface is the "zone of aeration", where gaps between soil are filled with both air and water. Below this layer is the "zone of saturation", where the gaps are filled with water. The water table is the boundary between these two layers. As the amount of groundwater water increases or decreases, the water table rises or falls accordingly. When the entire area below the ground is saturated, flooding



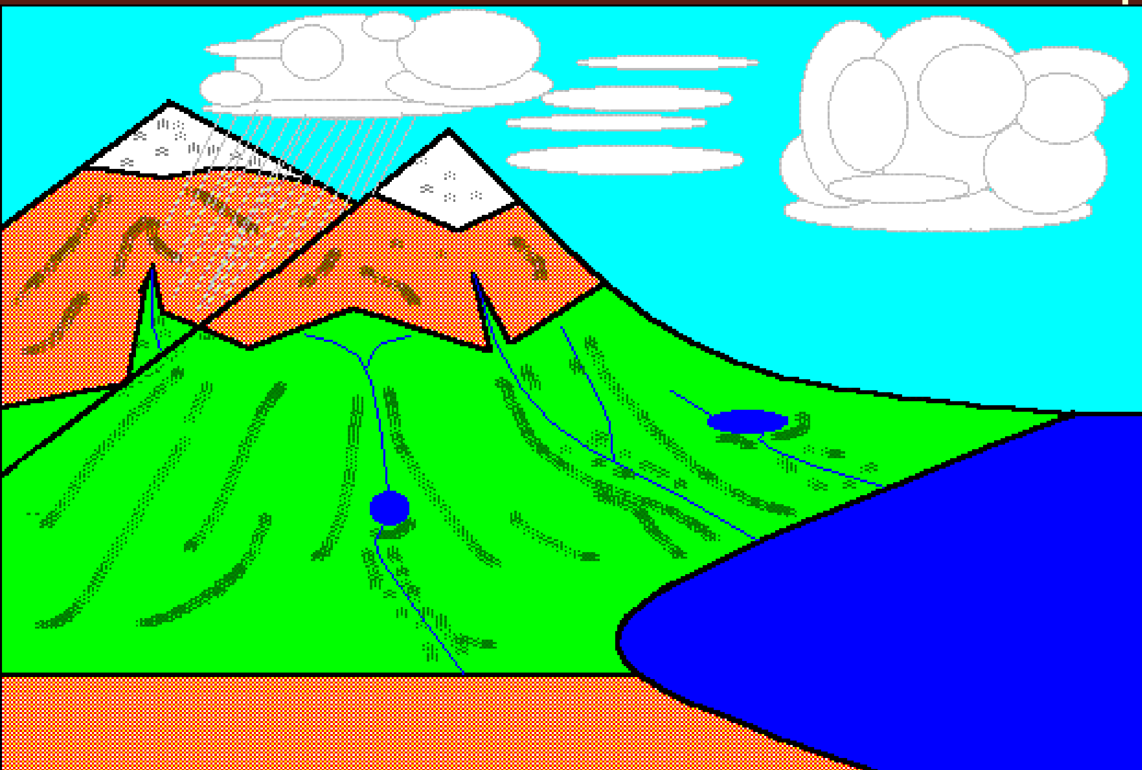
The amount of water that can be held in the soil is called "porosity". The rate at which water flows through the soil is its "permeability". Different surfaces hold different amounts of water and absorb water at different rates. Surface permeability is extremely important for hydrologists to monitor because as a surface becomes less permeable, an increasing amount of water remains on the surface, creating a greater potential for flooding. Flooding is very common during winter and early spring



Water that infiltrates the soil flows downward until it encounters impermeable rock (shown in gray), and then travels laterally. The locations where water moves laterally are called "aquifers". Groundwater returns to the surface through these aquifers (arrows), which empty into lakes, rivers, and the oceans. Under special circumstances, groundwater can even flow upward in artesian wells. The flow of groundwater is much slower

Transpiration

transfer of water from plants to the



Transpiration is the evaporation of water into the atmosphere from the leaves and stems of plants. Plants absorb soilwater through their roots and this water can originate from deep in the soil. (For example, corn plants have roots that are 2.5 meters deep, while some desert plants have roots that extend 20 meters into the ground). Plants pump the water up from the soil to deliver nutrients to their leaves. This pumping is driven by the evaporation of water through small pores called "stomates", which are found

Runo
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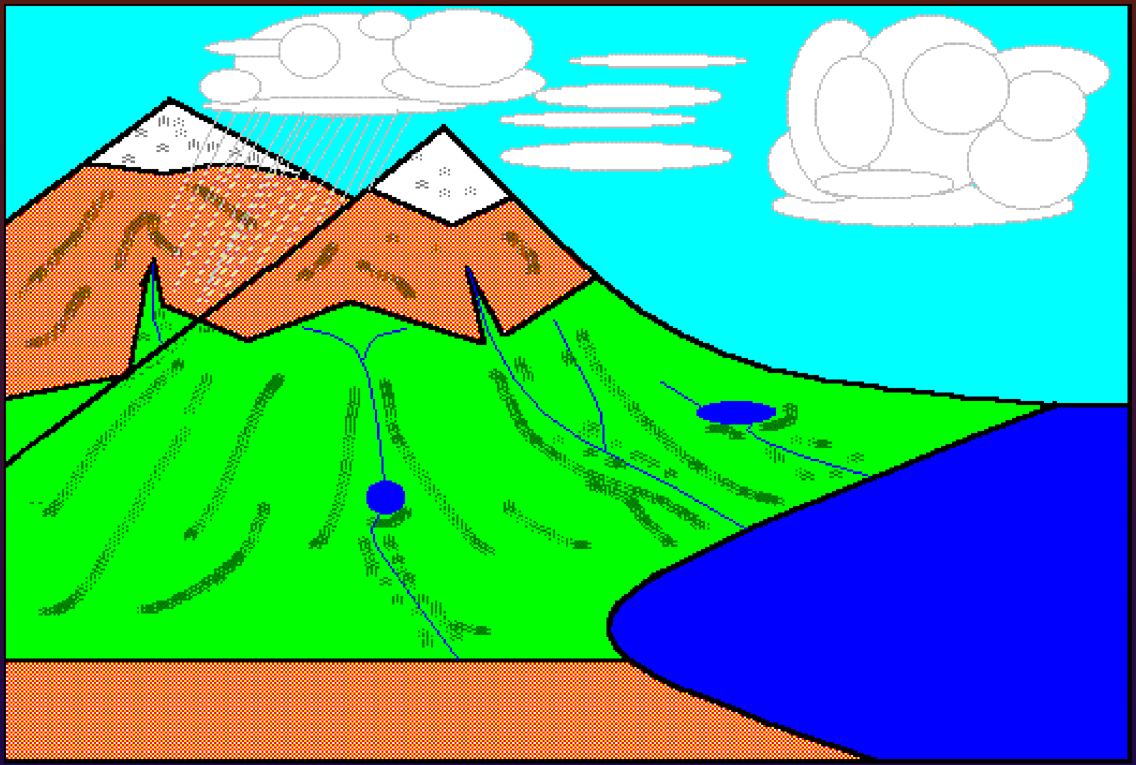
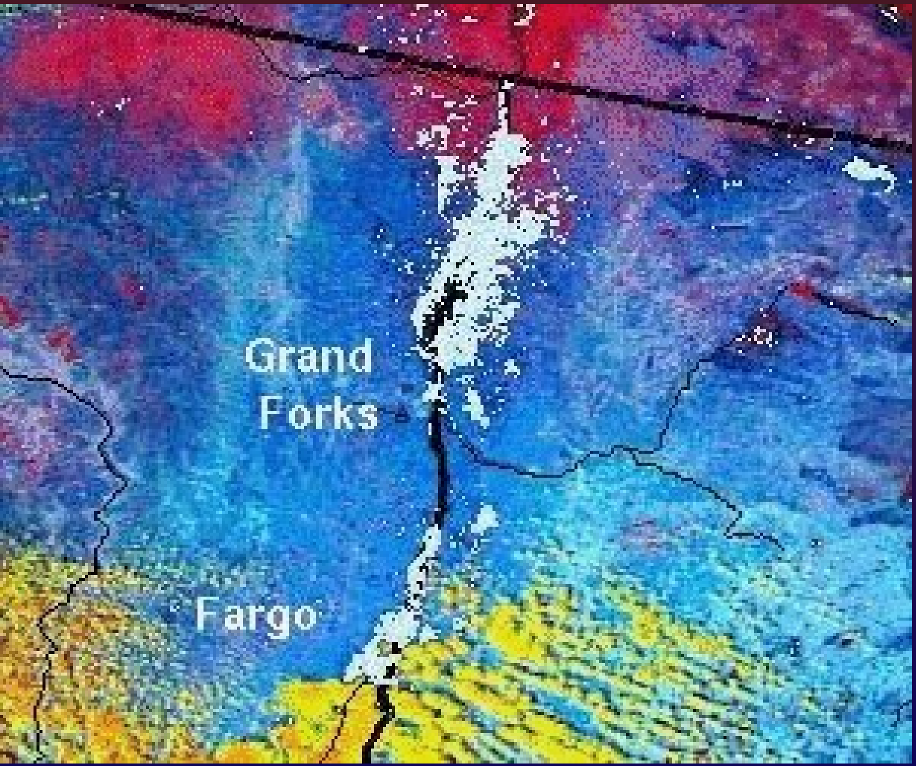
transfer of landwater to



Runoff is the movement of landwater to the oceans, chiefly in the form of rivers, lakes, and streams. Runoff consists of precipitation that neither evaporates, transpires nor penetrates the surface to become groundwater. Even the smallest streams are connected

Excess runoff can lead to flooding, which occurs when there is too much precipitation. Two recent events in the United States have caused major flooding.

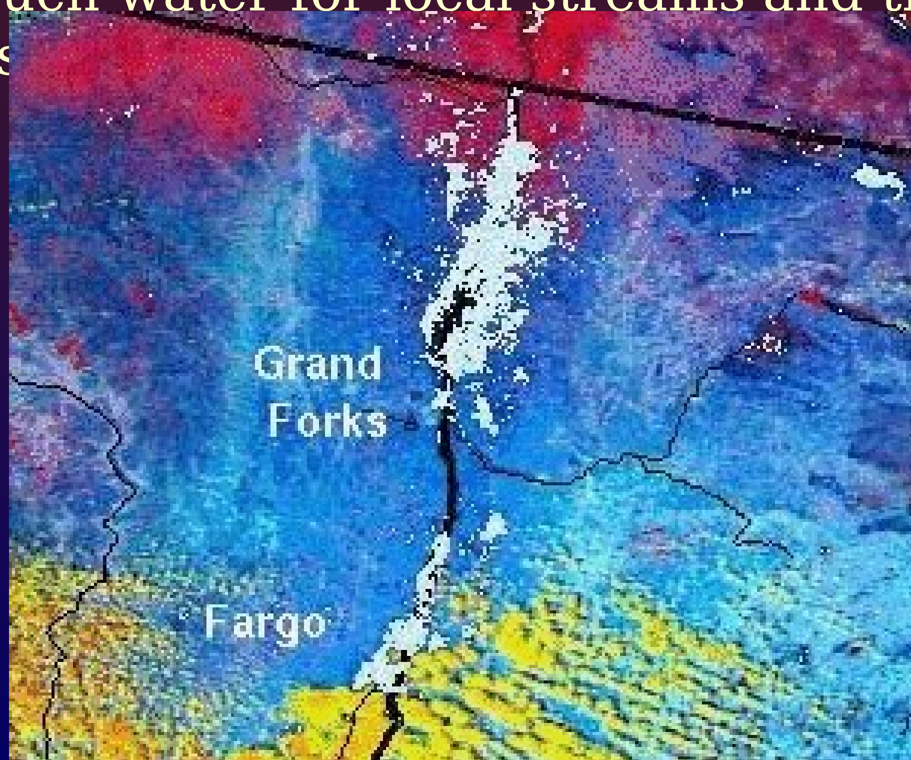


Northern Plains Flooding

March-May 1997

In early spring of 1997, the Northern Plains endured devastating floods. Towns along the Red River like Grand Forks, North Dakota were shut down due to flooding that completely paralyzed the city, leaving entire downtown areas underwater. Floodwater is shown here in white while unmelted snow is

During the Fall of 1996, towns along the Red River received record amounts of rain. In the winter, a cold air outbreak froze the water before it could runoff, and the record rainfall was followed up by record amounts of snow. Snow continued to pile up during the long winter and once temperatures finally warmed up, the melting began. However, not only did the snow from the winter melt, but also the frozen rainwater from the previous Fall season. As it turned out, there was too much water for local streams and the Red River to handle, and cons



River levels rose to as much as 27 feet above flood stage! Large pieces of floating ice blocked the flow of the river, forcing it out of its banks and into nearby residences and businesses.

Midwest Flooding

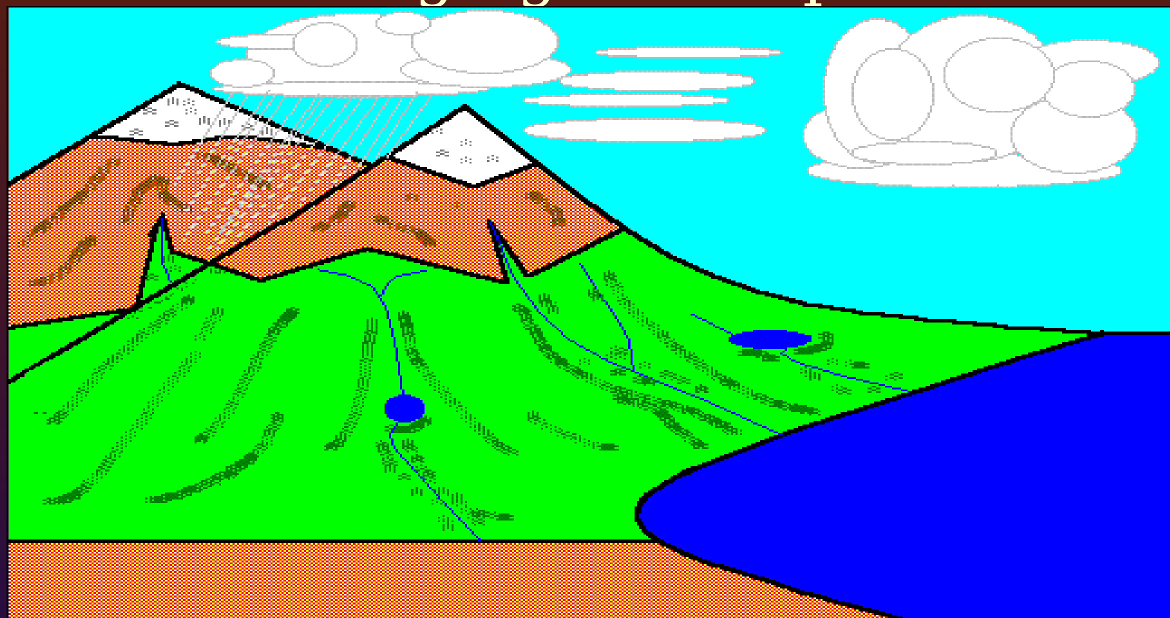
June-August 1993

During the summer of 1993, over 20 inches of rain fell upon many locations in the Midwest, with localized amounts exceeding 33 inches. The excessive amounts of rain severely affected shipping, agriculture, and human lives. This photo was taken in Ames, Iowa when the flood waters reached their maximum.

An analysis of atmospheric conditions for the summer of 1993 showed a stationary high pressure system, also known as the Bermuda High, centered much closer to the United States than normally observed for that time of year. This allowed unusual amounts of warm moist air to be transported northward from the Gulf of Mexico and into the central portion of the country. This moisture-rich air fueled showers and thunderstorms that brought significant amounts of rain to many regions of the Midwest. Precipitation totals were so large and of such extended duration that

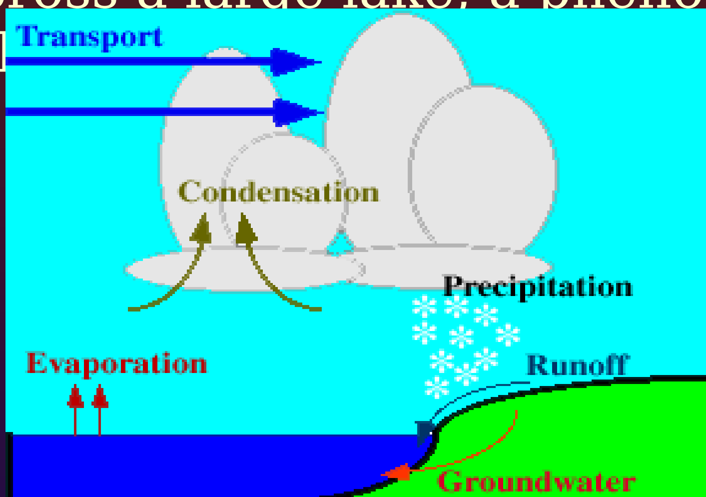
A Summary of the Hydrologic Cycle

bringing all the pieces



The hydrologic cycle begins with the evaporation of water from the surface of the ocean. As moist air is lifted, it cools and water vapor condenses to form clouds. Moisture is transported around the globe until it returns to the surface as precipitation. Once the water reaches the ground, one of two processes may occur; 1) some of the water may evaporate back into the atmosphere or 2) the water may penetrate the surface and become groundwater. Groundwater either seeps its way to into the oceans, rivers, and streams, or is released back into the atmosphere through transpiration. The balance of water that remains on the earth's surface is runoff, which

Lake effect snowfall is good example of the hydrologic cycle at work. Below is a vertical cross-section summarizing the processes of the hydrologic cycle that contribute to the production of lake effect snow. The cycle begins as cold winds (horizontal blue arrows) blow across a large lake, a phenomena that occurs frequently in the late fal nd the Great Lakes.



Evaporation of warm surface water increases the amount of moisture in the colder, drier air flowing immediately above the lake surface. With continued evaporation, water vapor in the cold air condenses to form ice-crystal clouds, which are transported toward shore.

By the time these clouds reach the shoreline, they are filled with snowflakes too large to remain suspended in the air and consequently, they fall along the shoreline as precipitation. The intensity of lake effect snowfall can be enhanced by additional lifting due to the topographical features (hills) along the shoreline. Once the snow begins to melt, the water is either absorbed by the ground and becomes groundwater, or goes returns back to the lake as runoff.

Lake effect snow events can produce tremendous amounts of snow. One such event was the Cleveland, Ohio Veteran's Day Snowstorm from November of 1996, where local storm snowfall totals exceeded 50 inches